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# STUDY OF DIC HYDROTHERMAL TREATMENT EFFECT ON RHEOLOGICAL PROPERTIES OF STANDARD MAIZE (SMS), WAXY MAIZE (WMS), WHEAT (WTS) AND POTATO (PTS) STARCHES

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**Keywords:** Starch, DIC hydrothermal treatment, Granulometry, Rheological properties.

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## 1 1. Abstract

2 Standard maize (SMS), waxy maize (WMS), wheat (WTS) and potato (PTS) starches were  
3 hydrothermally treated by Instantaneous Controlled Pressure Drop (DIC) process at different  
4 pressure levels (1, 2 and 3 bar) corresponding to the temperatures of 100, 122 and 136°C,  
5 respectively. The rheological properties and particle size of treated starches under various  
6 conditions were compared to the native ones. The results showed for all starches, except for  
7 WTS, a reduction of the consistency coefficient and the yield stress ( $\tau_o$ ) with increased  
8 intensity of the hydrothermal treatment conditions. Furthermore,  $\tau_o$  vanished for severe  
9 treatment conditions. The DIC treatment yielded an increased fluidity and a loss of the  
10 conservative modulus of the pastes, as a result of partial gelatinization of starch granules. The  
11 extent of the observed effect depended on the botanical origin. Wheat starch exhibited a  
12 different behaviour: the consistency coefficient and the conservative modulus being higher for  
13 DIC treated starch except for the most severe conditions.

## 14 2. Introduction

15 Starch has many applications in food and non-food industries. As an ingredient, it is extracted  
16 from only a few species such as maize, wheat, potato, rice, tapioca, and sago. Pregelatinized  
17 starches have been widely used for many foods as a major ingredient to provide thickened  
18 textures at temperatures below the gelatinization temperature. They are obtained from native or  
19 modified starch, by drum drying (Vallous et al., 2002) or by extrusion cooking (Barron et al.,  
20 2000). Other processes of physical modification have been explored to improve qualities of the  
21 starch such as annealing (Tester et al., 2000; Jayakody and Hoover, 2008) and heat moisture  
22 treatment (HMT) (Kulp and Lorenz, 1981; Hoover and Manuel, 1996; Jacobs, et al., 1998;  
23 Collado and Corke, 1999; Tester et al., 2000; Gunaratne and Hoover, 2002; Vermeylen et al.,  
24 2006; Tukomane et al., 2007; Gunaratne and Corke, 2007, Chung et al., 2009). These two latter  
25 treatments differ in the water content, temperature and processing time used. Annealing occurs  
26 under large excess of water (50 to 60%) and relatively low temperatures (below the  
27 gelatinization temperature), while the HMT is conducted under restricted moisture content (10-  
28 30%) and higher temperatures (90-120 °C). Both treatments are applied over large periods of  
29 time (10-16h). The main effects of HMT are loss of birefringence, increased gelatinization  
30 temperature, broadened or unchanged gelatinization temperature range, change in X-ray  
31 diffraction patterns, reduced swelling volume and solubility, with consequent changes in  
32 functionality (Donovan et al., 1983; Collado and Corke, 1999; Gunaratne and Hoover, 2002).  
33 Annealing results in improved perfection of the crystallites within starch granules that narrows  
34 the gelatinization temperature interval; consequently, gelatinization temperatures shifted  
35 towards higher values (Hublin, 1994; Jacobs et al., 1998; Tester et al., 2000). The enthalpy of  
36 gelatinization remains unchanged or is moderately increased depending upon annealing  
37 conditions (moisture content and time) and the botanic origin (Karlsson and Eliasson, 2003;  
38 Lawal, 2005; Jayakody and Hoover, 2008) in contrast to HMT. The semi-crystalline structure

of starch granules is modified by these two usual physical treatments without disrupting the integrity of granule (Lim et al., 2001).

HMT starches have generally been performed at the laboratory scale and many authors have reported that such conditions produce inhomogeneous samples with lumps of gelatinized starch beside heat-moisture treated starch. For this reason, pressure is often required to ensure sufficient heating. To obtain a uniform heat distribution and rapid penetration of steam into the starch granules, Maruta et al. (1994) improved the conventional method by creating a reduced pressure in the vessel before the injection of live steam. This method was designated by these authors as the reduced-pressurized heat moisture treatment (RP-HMT).

The DIC treatment (Instantaneous Controlled Pressure Drop) has been developed at the laboratory as well as the pilot scale (Rezzoug et al., 2000), for drying and texturizing of food products such as pasta products (Maache-Rezzoug and Allaf, 2005). As for the RP-HMT process, an initial vacuum is applied before the treatment which is performed under high temperature/high steam pressure; the hydro-treatment step is then followed by an abrupt pressure drop towards vacuum pressure contrary to the RP-HMT treatment. This step induces a rapid modification of the thermodynamic equilibrium reached during the pressurisation ( $P_1, T_1$ ) towards another equilibrium state ( $P_2, T_2$ ). This new state induces a rapid cooling and the resulting temperature value depends on the vacuum pressure level (Zarguilli et al., 2009). The originality of the DIC process compared to other hydrothermal treatments is that starch is treated at an initial moisture content of 12.5% (wet basis), no hydration step being then used. During the treatment, the heating of starch is obtained by the absorption of latent heat of steam condensation which causes an increase in the moisture content as the processing time and pressure level increase (Zarguilli et al., 2009).

The major effects observed after DIC treatment are almost similar to HMT treatment except that the gelatinization temperature range is narrowed as observed with annealing (Hublin, 1994;

Jayakody and Hoover, 2008). This result suggests that the treatment firstly induced the melting of crystallites of low cohesion (low stability) which required less energy to melt. Consequently, the residual structure after the DIC treatment contained crystallites with a greater stability (cohesion) (Maache-Rezzoug et al., 2008). Preliminary studies on standard and waxy maize starches (Loisel et al., 2006, Zarguili et al., 2006) showed that the thermal properties of DIC treated starch depend on the processing time and the steam pressure level. Increasing these two parameters induces an increase in the onset ( $T_{\text{onset}}$ ) and in the peak ( $T_{\text{peak}}$ ) temperatures of gelatinization and a reduction in gelatinization enthalpy. The occurrence of a partial or total gelatinization was clearly attested by the decrease of enthalpy and a loss of birefringence under polarized light. The X-ray diffraction pattern confirmed the partial or total loss of the crystalline structure of native starch depending on the conditions of the DIC treatment: the relative crystallinity of hydrothermally treated maize starch decreased and the polymorphic type changed. The A-type crystalline pattern was progressively lost with the increase of processing pressure ( $\geq 2$  bar), and was substituted by the  $V_h$ -type X-ray diffraction pattern, corresponding to the formation of amylose-lipid complexes. At severe DIC conditions (pressure level of 3 bar), the typical peaks of A-type X-ray diffraction pattern were substituted completely by the ones of the  $V_h$ -type pattern (Maache-Rezzoug et al., 2008).

The objective of the present study was to describe the rheological properties of hydrothermally treated starches in the DIC process in relation to starch granules properties (size and size distribution, swelling behaviour). This study was based on rheological measurements (viscosity and viscoelasticity). These effects were investigated on starches of different origins: standard maize (SMS), waxy maize (WMS), wheat (WTS) and potato (PTS); identical treatments conditions (processing pressure and time) were applied, except for PTS. Lower pressure/time conditions were applied to potato starch due to its higher sensitivity to hydrothermal treatment.

## 88 3. Materials and methods

### 89 3.1. Materials

90 Standard maize starch (SMS), waxy maize starch (WMS, Waxilys 200), wheat starch (WTS)  
91 and potato starch (PTS) were supplied by Roquette Frères (Lestrem, France). The moisture  
92 content of these starches during the treatment was about 12% wet basis.

### 93 3.2. Methods

#### 94 3.2.1. *Moisture content*

95 The starch moisture content was determined by air oven at 105 °C during 24 h, according to the  
96 A.F.N.O.R (NF V03-707, 2000) standard method and related to the wet basis (% , wb).

#### 97 3.2.2. *DIC hydrothermal treatment*

98 The equipment and procedure of DIC hydrothermal treatment were largely described in  
99 previous studies (Zarguili et al., 2006). During the treatment, 22 g of starch (12.5%, wet basis)  
100 disposed in circular containers were placed in the processing vessel (12L) in a layer of 20 cm  
101 diameter and 0.5 cm height. An initial vacuum of 50 mbar was established. As demonstrated by  
102 Zarguili (2006), this initial vacuum **allows the air resistance to be reduced** and thus facilitates  
103 the diffusion of steam into the product, consequently a rapid heating is obtained. Saturated  
104 steam is introduced into the vessel at a fixed pressure level (1 to 3 bars) and maintained during  
105 a determined processing time. In this study the processing pressure was fixed at 1 bar (100 °C),  
106 2 bar (122 °C) and 3 bar (135 °C). The pressurisation is followed by an abrupt decompression  
107 towards vacuum (50 mbar). After the vacuum phase, atmospheric air is injected to return to  
108 atmospheric pressure for sample recovery. During the treatment, starch is heated by the  
109 absorption of latent heat of vapour condensation and its moisture content is increased.

### 3.2.3. *Pasting procedure using the Brabender Viscograph*

The DIC treated starches were pasted with demineralised water using a Brabender Viscograph in order to obtain starch pastes under repeatable conditions. The starch concentrations were chosen to lie within the sensitivity range of the Viscograph, depending on the botanical origin of starches. The concentrations used were 6%, 4%, 7% and 2% for SMS, WMS, WTS and PTS, respectively. The suspension was heated at 1.5 °C/min from 50 to 95 °C, then kept for 20 min at the plateau temperature and subsequently cooled down to 70 °C at 1.5 °C/min before immediate characterisation. The starch concentration was checked by drying the suspensions as previously described (3.2.1.).

### 3.2.4. *Granule size distribution*

Granule size determination was carried out at room temperature using a Malvern Master Sizer (Malvern Instruments, Ltd) laser scattering analyser with a 300 mm Fourier cell (range 0.05-879 µm). The starch dispersion was first diluted (1/10) with demineralised water at 20°C before and immediately after the pasting procedure in the Brabender Viscograph, and then dispersed into the sample dispersion unit (1ml/100ml water). The measure was repeated three times. The volume distribution was obtained according to the Mie scattering theory (Loisel et al., 2006). From each distribution, the median volume diameter ( $D_{v,0.5}$ ) was presented and the swelling ratio was defined as  $(D/D_0)^3$ , with D and  $D_0$  the median diameters of treated and native starch, respectively (Nayouf et al., 2003); the size distribution was evaluated using the dispersion index referred to as the span, by the following equation:

$$Span = \frac{D(v,0.9) - D(v,0.1)}{D(v,0.5)} \quad (\text{Eq.1})$$



### 3.2.5. *Rheological properties*

Flow behaviour and viscoelastic properties of starch pastes were measured at 60 °C (to avoid retrogradation) using a controlled stress rheometer (TA Instrument AR1000) with the cone/plate geometry (6 cm/2°). The starch dispersions at 60 °C were poured onto the preheated plate of the rheometer, and then covered by a thin layer of paraffin oil on the edge of the sample to avoid evaporation. For flow measurements, an up-down shear scan from 0 to 660 s<sup>-1</sup> (4 min) was linearly applied, followed by a logarithmic stepwise decrease from 660 to 0.01 s<sup>-1</sup>, after equilibrium for each shear rate. The oscillatory tests at 60 °C were carried out on a new aliquot at 4% strain (linear viscoelastic range). The frequency range investigated was from 0.5 to 100 rad/s.

## 4. Results and discussion

### 4.1. Granule size distribution

The size distribution of starch granules was carried out before (Figure 1a) and after pasting (Figure 1b) in the Brabender Viscograph. Table 1 presents the variation of the median diameter  $D_{V,0.5}$ , the swelling ratio  $(D/D_0)^3$  and the span, which measures the volume distribution width of starch granules, for SMS, WMS, WTS and PTS.

Before pasting the native starches exhibit a narrow size distribution of the granules, the median diameter lying between 12.9 for SMS, the smaller starch granules, to 44.6 µm for PTS the larger ones with also a minor peak at approximately one micron. These values correspond to the usual starch granule size distribution. For DIC treated starches, the size distribution curves before pasting were shifted towards higher sizes and broadened as increasing DIC conditions, with large differences depending on botanical origin: SMS being more prone to swell than WMS and WTS showing a dramatic increase at 3bar/5min. For PTS only slight modifications

were observed due to the low intensity of the DIC conditions. A progressive increase of the median diameter with the intensity of the treatment is attested for all starches. The span values increased for SMS, WMS and WTS, after DIC treatment reflecting a widening of the granule size distribution. This was particularly important for SMS (Table 1) and is probably due to the presence of a third peak at approximately 200 microns (Figure 1) corresponding to aggregates of starch granules. The different evolution of the swelling ratio  $(D/D_0)^3$  clearly underlines the differences between starches: SMS and WTS present the highest swelling capacities at 3bar/5min of 105.7 and 327.6, respectively. Such a behaviour, particularly for WTS, reflects the cold swelling of DIC treated starch granules; it is not mentioned in the literature for HMT treated starches and has been ascribed to partial loss of cristallinity and subsequent enhanced capacity to hydration (Loisel et al., 2006).

After pasting, the size distribution curves (Figure 1) of all the native starches exhibit a shift towards larger sizes as expected. The 1bar/60min treated starches, SMS, WMS and WTS, present the same distribution curve as the native ones with smoothing of the minor peak for WMS. But the 2bar/60min and 3bar/5min treated SMS and WMS show the reverse tendency: a shift towards a lower starch granules size. For SMS and WMS the minor peak at one micron was converted into a larger one, at approximately 5  $\mu\text{m}$ , which disappeared for the most severe conditions for WMS. This peak may be attributed to a population of small starch granules that swell upon pasting or to the disruption of larger ones. The median diameters  $D_{V,0.5}$  (Table 1) increase for native starch after pasting as expected (from 12.9 to 41.1  $\mu\text{m}$ , 14.3 to 32.5  $\mu\text{m}$ , 19.8 to 36.6  $\mu\text{m}$  and 44.6 to 112.3  $\mu\text{m}$ ) for SMS, WMS, WTS and PTS, respectively. The DIC treated SMS and WMS starches present similar sizes to the native ones for the lowest DIC conditions (1bar/60min). For medium and high DIC conditions a progressive decrease is observed: the swelling ratio reaches 0.4 for SMS and WMS at 3bar/5min. This modification can be ascribed to concomitant processes of swelling and disruption of starch granules

encountered during the pasting process. For DIC treated SMS and WMS the disruption phenomenon may prevail owing to the sensitivity of starch granules induced by the treatment. WTS exhibited an outstanding behaviour, by increasing the size of starch granules for the most severe condition (swelling ratio 1.93 for 3bar/5min). These modifications of the starch granules size distribution by DIC treatment will obviously affect the rheological properties.

## 4.2. Rheological properties

Figure 2 presents the rheograms of native and DIC treated starches of SMS, WMS, WTS and PTS. The flow curves are typical of shear-thinning fluids, except the ones of samples treated at 2bar/60min and 3bar/5min for SMS, 3bar/5min for WTS and at 1.5bar/5min for PTS. We also observe the persistence of the thixotropic behaviour of the starches, which may result from a disruption of starch granules aggregates under shearing. This phenomenon appeared less pronounced when the treatment conditions increased and disappeared for samples treated at 3bar/5min for SMS and 1.5bar/5min for PTS.

The Herschel-Bulkley equation (Eq.2) was applied satisfactorily from the equilibrium curves (not presented in Figure 2) according to Eq. (2):

$$\tau = \tau_0 + k \dot{\gamma}^n \quad (\text{Eq.2})$$

$\tau$  is the shear stress (Pa),  $\dot{\gamma}$  is the shear rate ( $\text{s}^{-1}$ ),  $\tau_0$  is the yield stress (Pa),  $K$  is the consistency index ( $\text{Pa.s}^n$ ) and  $n$  is the flow behaviour index (dimensionless).

The values of the flow parameters ( $\tau_0$ ,  $K$ ,  $n$ ) and the apparent viscosity for  $1\text{s}^{-1}$  are given in Table 2. We observe shear-thinning behaviour ( $n < 1$ ) with a yield stress for all the native and treated starches except at 2bar/60min and 3bar/5min for SMS, 3bar/5min for WTS, and 1.5bar/5min for PTS. For these DIC conditions, the rheological behaviour of treated starches tended towards a Newtonian one with increasing flow behaviour index.

For WMS and WTS the flow behaviour index remains almost constant for all the process conditions. For all starches the increase of the process conditions causes a decrease of the yield stress and of the apparent viscosity except for WTS.

In Table 2 are presented the values of the storage modulus ( $G'$ ), and the loss modulus ( $G''$ ) measured at 60 °C. The suspensions of native starches exhibited the behaviour of a weak gel with  $G' > G''$  and  $G'$  almost independent of frequency (mechanical spectra, not shown).

The storage modulus  $G'$  sharply decreased for SMS as the process conditions became more intense, while the decrease was more progressive for WMS. This effect of the DIC process on the viscoelasticity of SMS and WMS starch suspensions agrees with previous results (Loisel et al., 2006). WTS is the only starch which behaved in a different way, exhibiting an increase of the storage modulus with the processing conditions.

Considering the effect of the treatment on the global properties of the starch suspensions, we can observe the same evolution between the rheological parameters (yield stress, viscosity, storage modulus, Table 2) and the size of the starch granules after pasting (Table 1): a tendency to a decrease for SMS, WMS and PTS and to an increase for WTS with the intensity of the treatment. But no direct relationship can be drawn between these two characteristics as the volume fraction of starch granules is not taken into account. It is well known that the rheological behaviour of a pasted starch suspension is the result of two main characteristics: the viscosity of the continuous phase and the volume fraction of the dispersed phase constituted by the starch granules (Doublier et al., 1987). The concentrations of the starch suspensions used in that study are very close to the packing concentration described by Steeneken (1989): i.e. the suspension can be assimilated to a packing of swollen starch granules that are responsible for the overall rheological properties of the suspensions, the contribution of the continuous phase being minored. In such a concentrated system, the storage modulus indirectly measures the rigidity of the swollen granules. The decrease of the storage modulus for SMS and WMS

resulting from the intensity of the treatment may reflect either a loss of rigidity of starch granules; or more probably a decrease of their volume fraction.

The DIC process presents some similarities with the HMT treatment as it is conducted at low moisture content between 15 and 20% for DIC (depending on the pressure) compared to the 30% usually used for HMT. All the authors state a decrease of the swelling factor (generally expressed as the volume of swollen granules to the volume of the dry starch) and of the Brabender viscosity after pasting and for SMS (Chung et al., 2009) and in a lesser extent for WMS (Hoover and Manuel, 1996; Gunaratne and Corke, 2007). PTS presents the greatest sensitivity to the HMT treatment according to these two characteristics (Gunaratne and Hoover, 2002) while WTS exhibits a decrease of the swelling factor but a minor viscosity loss (Gunaratne and Corke, 2007) or even a slight increase of the viscosity after pasting (Hoover and Vasanthan, 1994). The effect of the DIC treatment on the rheological properties of starch suspensions seems similar to a certain extent to the one of HMT treatment.

## 5. Conclusion

This study has shown that the rheological and morphological properties of starches from different botanical origins, standard maize (SMS), waxy maize (WMS), wheat (WTS) and potato (PTS), are influenced to a different extent by the processing conditions applied during the DIC treatment. The PTS is more sensitive to the treatment than other starches, whereas WMS and WTS are more resistant. When the processing treatments are intense the size distributions of the starch granules and the rheological properties of starch suspensions vary. We observed a reduction in swelling for SMS and WMS starch granules after pasting which was ascribed to their prevailing disruption. For WTS the reverse result was observed. The rheological behaviour tends to Newtonian behaviour ( $n=1$ ), except for WMS, with a decrease of the yield stress and the apparent viscosity as the processing conditions increase. The

252   rheological properties are related to the evolution of the size of starch granules with the DIC  
253   treatment.

## 254 6. REFERENCES

- 255 Barron, C., Buléon, A., Colonna, P., & Della Valle, G. (2000). Structural modifications of low  
256 hydrated pea starch subjected to high thermomechanical processing. *Carbohydrate Polymers*,  
257 43, 171-181.
- 258 Collado, L. S., & Corke, H. (1999). Heat-moisture treatment effects on sweet potato starches  
259 differing in amylose content. *Food Chemistry*, 65, 329-346.
- 260 Chung, H.J., Hoover, R., & Liu, Q. (2009). The impact of single and dual hydrothermal  
261 modifications on the molecular structure and physicochemical properties of normal corn  
262 starch. *International Journal of Biological Macromolecules*, 44, 203-210.
- 263 Donovan, J.W., Lorenz K., & Kulp K. (1983). Differential scanning calorimetry of heat  
264 moisture treated wheat and potato starches. *Cereal Chemistry*, 60, 381-387.
- 265 Doublier, J.L., Llamas, G., & Le Meur, M. (1987). A rheological investigation of cereal starch  
266 pastes and gels. Effect of pasting procedures. *Carbohydrate Polymers*, 7, 251-275.
- 267 Gunaratne, A., & Corke, H. (2007). Effect of hydroxypropylation and alkaline treatment in  
268 hydroxypropylation on some structural and physicochemical properties of heat-moisture  
269 treated wheat, potato and waxy maize starches. *Carbohydrate Polymers*, 68, 305-313.
- 270 Gunaratne, A., & Hoover, R. (2002). Effect of heat-moisture treatment on the structure and  
271 physical properties of tuber and root starches. *Carbohydrate Polymers*, 49, 425-437.

- 272 Hoover, R., & Manuel. H. (1996). Effect of heat-moisture treatment on the structure and  
273 physicochemical properties of normal maize, waxy maize, dull waxy maize and amylo maize  
274 V starches. *Journal of Cereal Science*, 23, 153-162.
- 275 Hublin, L. (1994). Influence des caractéristiques structurales des amidons natifs sur leur  
276 réactivité chimique. PhD dissertation, Université de Nantes. France.
- 277 Jacobs, H., Mischenko, N., Koch, M. H. J., Eerlingen, R. C, Delcour. J. A., & Reynaers, H.  
278 (1998). Evaluation of the impact of annealing on gelatinisation at intermediate water content  
279 of wheat and potato starches: A differential scanning calorimetry and small angle X-ray  
280 scattering study. *Carbohydrate Research*, 306, 1-10.
- 281 Jayakody, L., & Hoover, R. (2008). Effect of annealing on the molecular structure and  
282 physicochemical properties of starches from different botanical origins – A review.  
283 *Carbohydrate Polymers*, 74, 691-703.
- 284 Karlsson, M.E., & Eliasson, A.-C. (2003). Gelatinization and retrogradation of potato  
285 (*Solanum tuberosum*) starch in situ as assessed by differential scanning calorimetry (DSC)  
286 *Lebensmittel-Wissenschaft und-Technologie/FST*, 36 (8), 735-741.
- 287 Kulp, K., & Lorenz, K. (1981). Heat-moisture treatment of starches. I- Physicochemical  
288 properties. *Cereal Chemistry*, 58, 46-48.
- 289 Lawal, O.S. (2005). Studies on the hydrothermal modifications of new cocoyam (*Xanthosoma*  
290 *sagittifolium*) starch. *International Journal of Biological Macromolecules*, 37 (5), 268-277.
- 291 Lim, S. T., Chang, E. H., & Chung, H. J. (2001). Thermal transition characteristics of heat–  
292 moisture treated corn and potato starches. *Carbohydrate Polymers*, 46, 107-115.



- 293 Loisel, C., Maache-Rezzoug, Z., Esneault, C., & Doublier, J. L. (2006). Effect of  
294 hydrothermal treatment on the physical and rheological properties of maize starches. *Journal*  
295 *of Food Engineering*, 73, 45-54.
- 296 Maache-Rezzoug, Z., Zarguili, I., Loisel, C., Queveau, D., & Buléon, A. (2008). Structural  
297 modifications and thermal transitions of standard maize starch after DIC hydrothermal  
298 treatment. *Carbohydrate Polymers*, 74, 802-812.
- 299 Maache-Rezzoug, Z., & Allaf, K. (2005). Study of the effect of hydrothermal process  
300 conditions on pasta quality. *Journal of Cereal Science*, 41, 267-275.
- 301 Maruta, I., Kurahashi, Y., Takayano, R., Hayashi, K., Yoshino, Z., Komaki, T., & Hara, S.  
302 (1994). Reduced-pressurized heat-moisture treatment. A new method for heat-moisture  
303 treatment of starch. *Starch/Stärke*, 46, 177-181.
- 304 Nayouf, M., Loisel, C., & Doublier, J.L. (2003). Effect of thermomechanical treatment on the  
305 rheological properties of crosslinked waxy corn starch. *Journal of Food Engineering*, 59, 209-  
306 219.
- 307 Rezzoug, S.A., Maache-Rezzoug, Z., Mazoyer, J., Jeannin, M., & Allaf, K. (2000). Effect of  
308 instantaneous controlled pressure drop process on hydration capacity of scleroglucan.  
309 Optimisation of operating conditions by response surface methodology. *Carbohydrate*  
310 *Polymers*, 42, 73-84.
- 311 Steeneken, P.A.M. (1989). Rheological properties of aqueous suspensions of swollen starch  
312 granules. *Carbohydrate Polymers*, 11, 23-42.

- 313 Tester, R. F., Debon, S. J. J., & Sommerville, M. D. (2000). Annealing of maize starch.  
314 *Carbohydrate **Polymers***, 42, 287-299.
- 315 Tukomane, T., Leerapongnum, P., Shobsngob, S., & Varavinit, S. (2007). Preparation and  
316 characterization of annealed-enzymatically hydrolyzed tapioca starch and the utilization in  
317 tableting. *Starch/Stärke*, 59(1), 33-45.
- 318 Vallous, N. A, Gavrielidou, M.A., Karapantsios, T.D., & Kostoglou, M. (2002). Performance  
319 of a double drum dryer for producing pregelatinized maize starches. *Journal of Food*  
320 *Engineering*, 51, 171-183.
- 321 Vermeulen, R., Goderis, B., & Delcour, J. A. (2006). An X-ray study of hydrothermally treated  
322 potato starch. *Carbohydrate **Polymers***, 64, 364-375.
- 323 Zarguili, I. (2006). Etude de l'effet de l'hydrotraitement DIC sur les propriétés structurales et  
324 fonctionnelles des amidons de différentes origines botaniques. PhD dissertation, University of  
325 La Rochelle. France
- 326 Zarguili, I., Maache-Rezzoug, Z., Loisel, & C., Doublier, J.-L. (2006). Influence of DIC  
327 hydrothermal process conditions on the gelatinization properties of standard maize starch.  
328 *Journal of Food Engineering*, 77 (3), 454-461.
- 329 Zarguili, I., Maache-Rezzoug, Z., Loisel, C., & Doublier, J.-L. (2009). A mathematical model  
330 to describe the change of moisture distribution in maize starch during DIC hydrothermal  
331 treatment. *International Journal of Food Science and Technology*, 44, 10-17.

## Figures Captions

**Figure 1:** Size distribution of native and DIC treated SMS, WMS, WTS, and PTS starches: (a) before pasting and (b) after pasting.

**Figure 2:** Flow curves of native and DIC treated starch dispersions measured at 60 °C after pasting, with starch concentration of 6%, 4%, 7% and 2% for SMS, WMS, WTS and PTS, respectively.

342 Figure 1

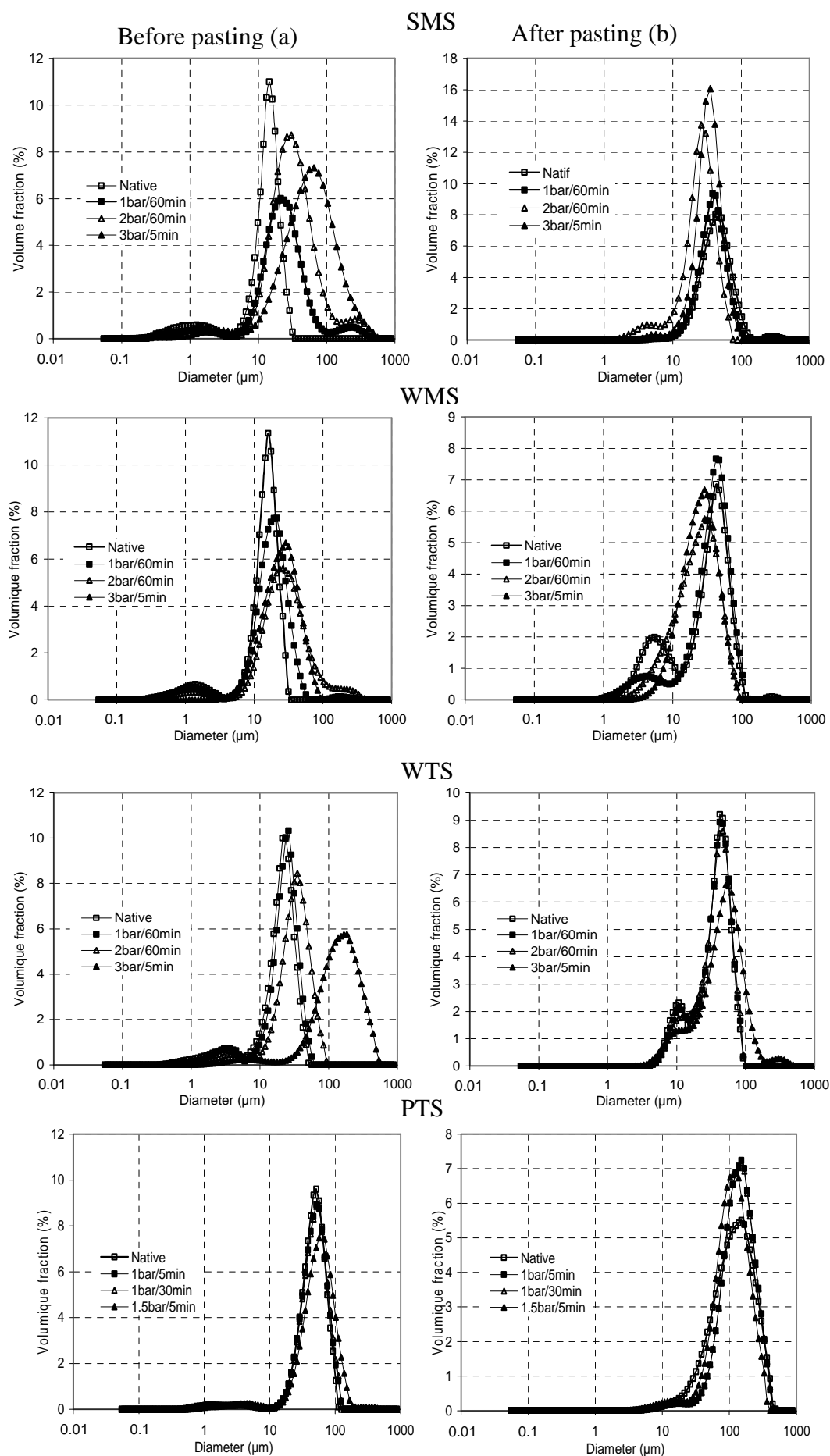
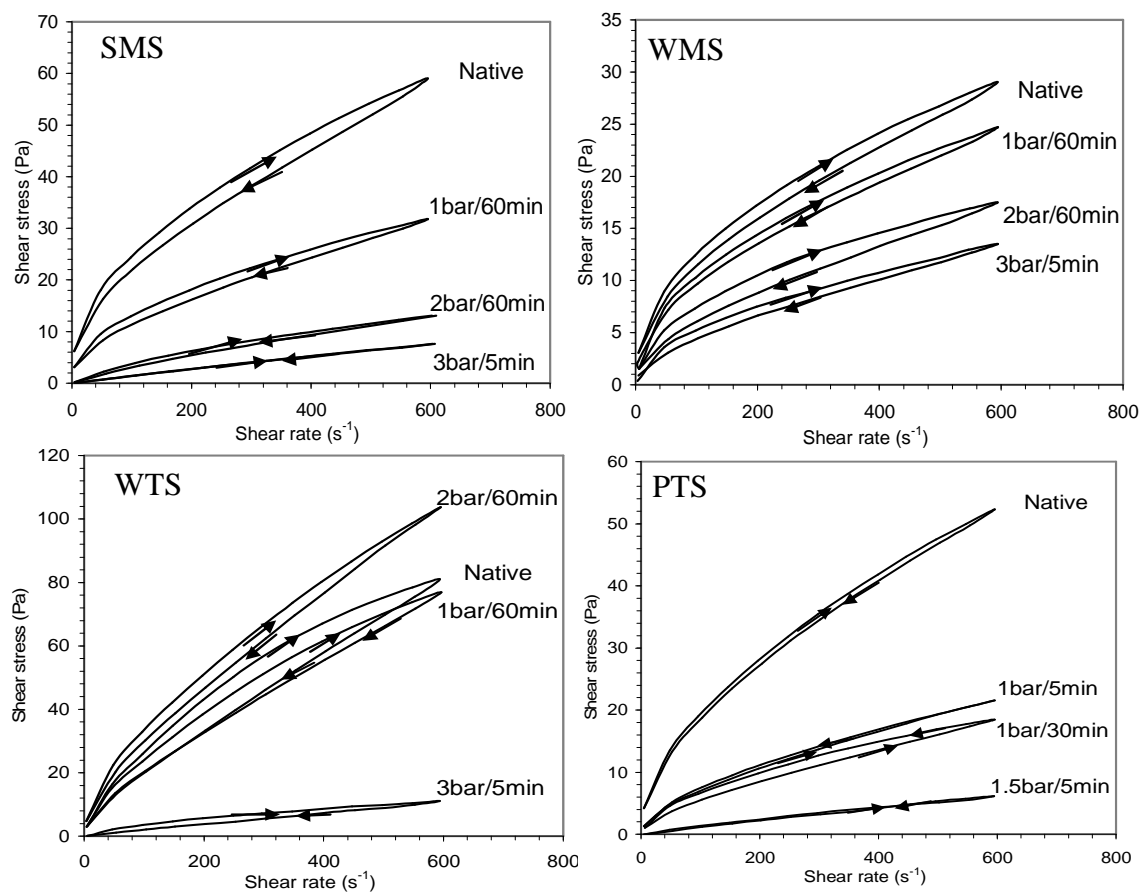


Figure 2



**Table 1:** Particle size characteristics of SMS, WMS, WTS and PTS after DIC treatment.  
(standard deviation of  $D_{V,0.5} = 0.3 \mu\text{m}$ )

Starch source	DIC conditions Pressure level/ processing time (bar/min)	Granulometry					
		Before pasting			After pasting		
		$D_{V,0.5}$ ( $\mu\text{m}$ )	$(D/D_0)^3$	Span	$D_{V,0.5}$ ( $\mu\text{m}$ )	$(D/D_0)^3$	Span
SMS	native	12.9	1.0	1.4	41.1	1.0	1.3
	1/60	19.3	3.3	1.5	39.3	0.9	1.2
	2/60	27.7	9.9	2.4	23.8	0.2	1.3
	3/5	61.0	105.7	2.5	29.6	0.4	1.8
WMS	native	14.3	1.0	1.1	32.5	1.0	1.8
	1/60	17.1	1.2	1.4	36.1	1.4	1.7
	2/60	25.3	5.5	2.4	22.5	0.3	1.8
	3/5	39.5	21.1	1.8	23.7	0.4	1.5
WTS	native	19.8	1.0	1.2	36.6	1.0	1.3
	1/60	22.2	1.4	1.2	36.8	1.0	1.3
	2/60	30.5	3.6	1.4	36.7	1.0	1.4
	3/5	136.5	327.6	1.8	45.6	1.9	1.8
PTS	native	44.6	1.0	1.2	112.3	1.0	1.9
	1/5	45.8	1.1	1.2	114.8	1.1	1.5
	1/30	46.4	1.1	1.2	114.4	1.1	1.5
	1.5/5	54.1	1.8	1.4	104.9	0.8	1.5

**Table 2:** Herschel-Bulkley parameters and viscoelastic properties of SMS, WMS, WTS and PTS pasted suspensions after DIC treatment.

DIC conditions		Flow behaviour 60°C				Viscoelasticity (60°C ;6.3 rad/s)		
Starch source	Pressure level / processing time (bar / min)	$\tau_o$ (Pa)	K (Pa.s <sup>n</sup> )	n	$\eta_a$ (Pa.s)	G' (Pa)	G'' (Pa)	Tan( $\delta$ )
SMS <sup>a</sup>	native	2.28	1.39	0.57	3.68	126.7	16.6	0.13
	1/60	0.68	0.72	0.58	1.41	115.4	13.4	0.12
	2/60	0.00	0.04	0.91	0.04	0.43	0.16	0.37
	3/5	0.00	0.01	1.00	0.01	3.12	0.91	0.29
WMS <sup>b</sup>	native	0.70	0.88	0.53	1.58	1.96	1.06	0.54
	1/60	0.71	0.81	0.52	1.52	1.69	0.93	0.55
	2/60	0.31	0.26	0.62	0.57	1.12	0.74	0.66
	3/5	0.36	0.58	0.54	0.95	1.20	0.90	0.75
WTS <sup>c</sup>	native	0.95	0.44	0.78	1.39	21.7	11.2	0.52
	1/60	0.87	0.75	0.70	1.63	30.1	12.8	0.45
	2/60	1.00	0.87	0.72	1.87	26.9	10.5	0.39
	3/5	0.00	0.03	0.88	0.03	63.5	12.4	0.19
PTS <sup>d</sup>	native	0.77	1.28	0.57	2.05	9.70	6.4	0.66
	1/5	0.06	0.47	0.60	0.53	3.90	2.5	0.64
	1/30	0.02	0.15	0.71	0.17	4.10	2.7	0.66
	1.5/5	0.00	0.02	0.89	0.02	0.34	0.04	0.11

<sup>a</sup> 6% (w/w) SMS suspension; <sup>b</sup> 4% (w/w) WMS suspension; <sup>c</sup> 7% (w/w) WTS suspension and <sup>d</sup> 2% (w/w) PTS suspension;  $\tau_o$  :yield stress ; K : consistency index; n : flow behaviour index ( $\tau_o$ , K and n were determined from Herschel-Bulkley model);  $\eta_a$ :apparent viscosity measured at 1s<sup>-1</sup>.